COOLING SYSTEM DESIGN OF COMPACT KLYSTRON MODULATOR POWER SUPPLY IN THE XFEL PROJECT AT SPring-8

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Abstract

XFEL project at SPring-8 requests the high performance modulator power supply for klystron i.e., low pulse-to-pulse fluctuation, low parameter drift, low noise, compact size, and easy maintenance [1]. To meet these requirements, we developed the compact klystron modulator power supply which stores the high voltage components in single steel tank. In order to obtain the practical heat transfer efficiency, we measured the heat transfer efficiency for various cooling panels in the model tank. Based on the results, we designed the optimum cooling system for the actual modulator power supply. We installed the cooling system to the modulator power supply, and confirmed the cooling efficiency was as expecting, and the oil temperature was under 45 °C.

THE KLYSTRON MODULATOR POWER SUPPRY AT XFEL/SPRING-8

In the XFEL/SPring-8 project, the electron beams are accelerated by 128 of C-band accelerating structures. Since the accelerator is compact thanks to the acceleration gradient as high as 35 MV/m, the interval lengths of the modulator power supply for klystron become narrow. Therefore, the size of the modulator should be more compact than traditional one. Consequently, we developed the compact modulator power supply for klystron, which stored the PFN condensers, a thyratron, and a pulse transformer in an oil-filled tank. The specification of the modulator is listed in table 1.

The insulation oil enabled the tank to be compact, and isolate the performance from dust and humidity. Otherwise, the cooling system of the oil is one of the most important points for the requirement of stable operation and maintenance-free. The modulator dissipates the heat mainly coming from a thyratron cathode heater, a klystron cathode heater, a pulse transformer, and electrical resistors. The excessive increase of the oil temperature by the heat generation leads the problems as written blow;

- The drifts of the electrical properties of the components.
- The drift of the air temperature by the heat dissipation from the modulator to the air.
- The deterioration of the insulation oil and the heat dissipation to the air.

To avoid the problems, we need the efficient cooling system which transfers the heat from the oil to the cooling water. We aimed for the cooling system not only efficient but also compact and maintenance-free. We chose the natural convection cooling, i.e. fan-less cooling.

In this paper, we described the review of the oil cooling, the efficiency of the fan-less cooling system, and the results of the oil temperature of the modulator in our prototype modulator.

Table1: Klystron modulator specifications

PFN charging voltage	45 kV
Output voltage	350 kV
Output current	316 A
Transformer step up ratio	1 : 16
Pulse width (at 70% of the voltage peak)	4.2 μsec
Peak output power	110 MW
Maximum repetition rate	60 pps

HEAT TRANSFER IN NATURAL CONVECTION

The oil flows by natural convection which occurs due to the heat transfer between oil and object. Around the heat sources, such as electric resistors or cathode heaters, the oil is heated and starts to rise. When the hot oil reaches to the cooling material, such as a water pipe or panel, the heat moves to the water and the oil sinks down.

The heat transfer rate q between the oil and the object can be written as,

$$q = hA(T_h - T_c) \tag{1}$$

where h is the heat transfer coefficient, A is area of the cooling material, T_h and T_c are the temperature of the hot object and the cold object, respectively. The heat transfer coefficient represents the cooling efficiency. The practical value of the coefficient is difficult to be calculated analytically, because it depends on not only the property of the oil but also the geometry of the panel and the detail flow around the object [2].

There are a few reports for the heat transfer coefficient for the insulation oil [3]. But, the conditions of the report differ from our condition in the oil type and the cooling panel geometry. Therefore, we performed the experiment to measure the coefficients.

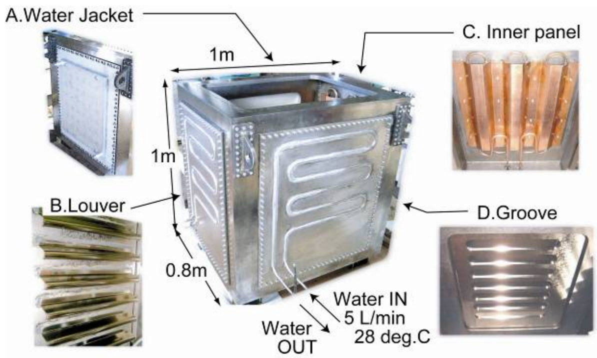

Figure 1: The model tank and the cooling panels.

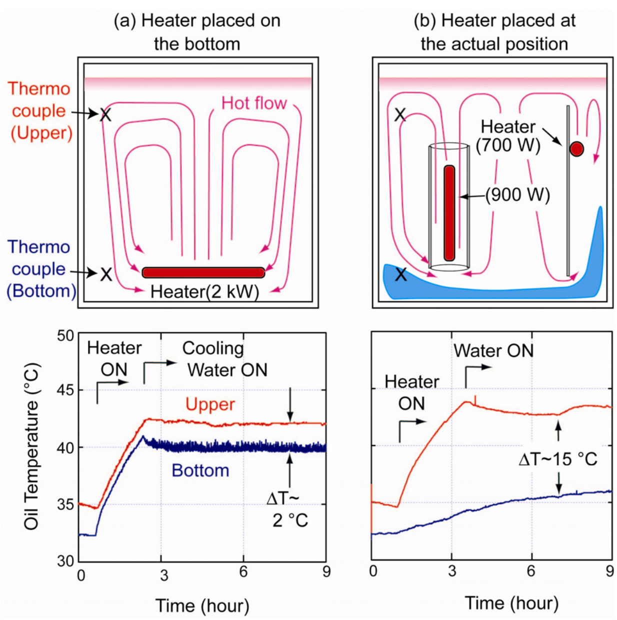

Figure 2: Upper figures show the schematic layouts of the experiments, and lower figures show the oil temperatures at the upper area and the bottom area of the model tank.

EXPERIMENTS OF THE COOLING PANELS IN THE TEST TANK

To obtain the practical heat transfer coefficient, the dimensions of the tank and the cooling panel demand to be close to the actual modulator. Consequently, we fabricated the model tank with the comparable size as the modulator. We designed the four cooling panels as shown in Fig. 1. The characteristic features for the panels are written below.

A) **Jacket type**; the water jacket on the plate is attached on whole area of the SUS flat panel.

B) **Louver type**; water pipe is built in a steel panel and copper louver is attached on inside of the panel. The louver mixes cold oil falling on the plate, and prevents the build-up of the layer of the cold viscous oil [3].

C) **Inner panel type**; the corrugated copper board jointing with the water pipe is installed inside of the tank.

Table 2: Heat transfer and heat transfer coefficient between the four cooling panels and the water.

Panel	Area (m^2)	Heat transfer (W)	Heat transfer Coefficient (W/m^2K)
A) Jacket	0.35	350	75
B) Louver	0.38	315	62
C) Inner Panel	0.42	665	130
D) Groove	0.42	385	69
Air	3.6	285	4.5

D) **Groove type**; water pipe is attached on the outside of the panel, and the inside surface is grooved. The groove mixes the oil and advances the heat transfer as same as the louver type.

In Fig. 2, we show the schematic layout of the experiments and the measurements oil temperature. At the setup (a), we placed the electric heater on the bottom of the tank, and heated the oil with 2 kW heat power. The flow rate of the cooling water was 10 L/min, and the water temperature was 28 °C. The heat transfer coefficients of the four cooling panels were estimated in the thermal equilibrium state; we estimated the heat flow from the oil to the panels by measuring the temperature difference between the water at enter and at exit, and assumed the cooling water temperature as the mean temperature between enter and exit, and the oil temperature as that in the upper oil. In table 2, the estimated heat transfer coefficients are summarized. The heat transfer coefficients of the panels with external water pipe, such as (A) Jacket, (B) Louver, and (D) Groove, are about 60-75 W/m^2K. The coefficient of the inner panel is 130 W/m^2K, which is twice as large as the others. It is assumed that the inner panel have the larger area contacting the oil than others.

At the setup (b), we measured the coefficients and the oil temperature in the situation similar to the actual modulator; one heater assumed the thyratron was placed vertically and heated up with 900 W, and the another heater assumed the EOL resistor was placed on the similar height and heated up with 700 W. In this experiment, the difference of the temperature between upper and bottom of the oil was larger than the previous experiments (setup (a)). It was explained that the oil flow was restricted around the heater and the upper of the tank. And the cold oil was fixed around the lower area because of the large viscosity of the oil. Therefore, the heat transfer between the oil and the panels was occurred only upper area, and the total heat transfer became small. The heat transfer coefficient of the inner panel was estimated to be about 91 W/m^2K, which was smaller than the previous setup.

This result shows that the cooling efficiency depends on not only the design of the cooling panel but also the position of heater. To enhance the cooling efficiency, the heater should be placed on the bottom. The heat transfer from oil to air was estimated to be 4.5 W/m^2K.

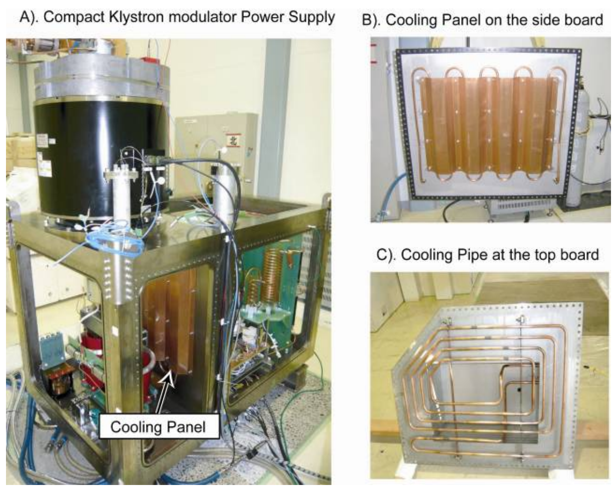

Figure 3: View of the compact klystron modulator, and the cooling system.

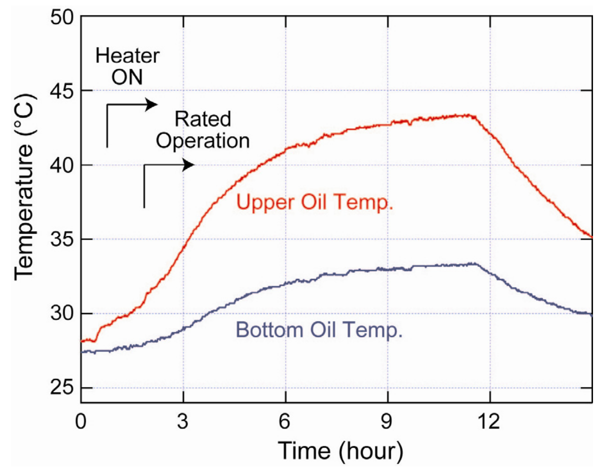

Figure 4: Oil temperature in the rated operation.

DESIGN OF THE COOLING SYSTEM FOR THE NEW MODULATOR

We designed the cooling system for the actual modulator based on the result of the test experiment. The heat generation in the modulator was estimated to be about 3 kW [4]. We aimed to suppress the oil temperature below 45 °C. The requirement cooling power which assumed the product of the heat transfer coefficient and the area, is calculated to be 178 W/K in the condition of the water flow rate is 8 L/min and the water temperature is 26 °C. Using the coefficient 91 W/m^2K, the total area is needed to be 2.2 m^2.

We designed the simple cooling system to satisfy the above request and to keep the easy maintenance. We installed it into the actual modulator. In Fig. 3, the view of the modulator and the cooling panel are represented.

1. Two inner panels (type C) attached on inside of the side panel
2. Two inner type panels (type C) attached both side of the partition wall.
3. One water pipe installed inside of the top panel.

The total cooling power was calculated as 210 W/K using the heat transfer coefficient and the total areas. The oil temperature in the actual modulator was predicted to be about 42 °C.

MEASUREMENTS OF THE TEMPRETURE OF THE MODULATOR

During the rated operation of the modulator, we measured the oil temperature of the oil. The temperature of the insulation oil is represented in figure 4. The temperature reached 43 °C in the upper area, and 34 °C in the lower area. The heat transfer from the oil to the water was calculated about 3 kW from the water temperature difference. Therefore, the total cooling power was estimated to be 214 W/K, which was nearly equal to the expected ability.

In addition, we also measured the temperature of the HV components. surface temperatures of the EOL resistance was 50 °C, thyratron anode was 45 °C and the outer case of thyratron cathode are 80 °C. Expect the out case of the thyratron cathode, the surface temperatures of these components were below the deteriorated temperature of the insulation oil. For the thyratron, we are going to improve the heat transfer.

The heat transfer to the air was calculated to be about 200 W at 26 °C air temperature. This heat dissipation is much smaller than that from other components.

SUMMARY

We performed the experiment to measure the heat transfer coefficients between the insulation oil and the cooling panels using the model tank. Based on the result, we designed the cooling system of the new modulator in XFEL/SPring-8. In the rated operation of the modulator, we confirmed the oil temperature was under 45 °C, and the cooling system performed as our expected. The modulator is in operation without problems.

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